Observation of PeV Gamma Rays from the Monogem Ring with the Tibet Air Shower Array

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ABSTRACT

We searched for steady PeV gamma-ray emission from the Monogem ring region with the Tibet air shower array from 1997 February to 2004 October . No evidence for statistically significant gamma-ray signals was found in a region $111^\circ \leq$ R.A. $< 114^\circ$, $12^\circ\!.5 \leq$ decl. $< 15^\circ\!.5$ in the Monogem ring where the MAKET-ANI experiment recently claimed a positive detection of PeV high-energy cosmic radiation, although our flux sensitivity is approximately 10 times better than MAKET-ANI's. We set the most stringent integral flux upper limit at a 99% confidence level of 4.0×10^{-12} cm^{-2} s^{-1} sr^{-1} above 1 PeV on diffuse

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gamma rays extended in the 3° × 3° region.

Subject headings: (stars:) supernovae: individual (Monogem Ring) — gamma rays : observations

1. Introduction

In a recent observation at PeV energies, the MAKET-ANI air shower experiment at Mount Aragats (E44°10′, N40°30′N; 3200 m above sea level) claimed a detection of significant excess (6σ) of cosmic-ray events within a 3° × 3° search window ($111° \leq \alpha < 114°$, $12.°5 \leq \delta < 15.°5$) in the Monogem ring region using the air shower data recorded from 1997 to 2003 (Chilingarian, Martirosian, & Gharagyozyan 2003) Naturally, the significant excess may be attributed to PeV gamma rays, because the Larmor radius $R_{\mathrm{L}} \sim 0.4 \,/\, Z$ pc at 10^{15} eV in the galactic magnetic field of 3 μG is too small to reach the Earth without deflection compared with the distance of 300 pc between the Earth and the Monogem ring, and the mean decay length of a neutron $\lambda \sim 10$ pc at 10^{15} eV is also too short.

The Monogem ring is a diffuse (extended with a diameter of 25° in the sky) supernova remnant (SNR) associated with the radio pulsar PSR B0656+14 at a distance of approximately 300 pc (Thorsett et al. 2003). This SNR is a bright source in the soft X-ray region. According to a detailed observation of the Monogem ring made by the *ROSAT* X-ray survey (Plucinsky et al. 1996), the average temperature of thermal emission is 6.15 in $\log(T/1\ \mathrm{K})$. If the Monogem ring is modeled as an SNR in the adiabatic stage of evolution, the initial ambient density is estimated to be 5.2×10^{-3} cm^{-3}, the initial explosion energy is estimated to be 1.9×10^{50} erg, the radius to the shock front is estimated to be 66.5 pc, and the age is estimated to be 86 thousand years. The Monogem ring has been considered to be a possible candidate for the particle acceleration site of cosmic electrons (Kobayashi et al. 2004) and nuclei (Thorsett et al. 2003) in our Galaxy.

The cosmic-ray flux we observe at the Earth roughly shows a power-law spectrum at energies from 10^9 to 10^{20} eV. There is a general consensus that the stochastic shock acceleration at SNRs in our Galaxy could explain the cosmic-ray energy spectrum up to approximately 10^{15} eV. The maximum energy is estimated to be only $\sim Z \times 10^{14}$ eV by parallel shock acceleration where the normal axis of shock front is parallel to the direction of the interstellar magnetic field. On the other hand, the oblique shocks accelerate particles more efficiently than the parallel shocks (Jokipii 1987). The maximum energy based on the oblique shock acceleration increases by several orders of magnitude, and could explain the cosmic-ray energy spectrum up to approximately 10^{17} eV (Kobayakawa et al. 2002). In

this case, the cosmic rays beyond 10^{17} eV are assumed to be of extragalactic sources, such as active galactic nuclei and gamma-ray burst . Among recent models, the "single source (SS) model" (Berezhko et al. 1996; Erlykin & Wolfendale 2004) is interesting in that a single nearby SNR, such as the Monogem ring, mainly contributes to the cosmic-ray intensity observed at the Earth. To explain the shape and intensity of the cosmic-ray energy spectrum using the SS model, the most likely parameters of the single SNR should be 300–350 pc distant and 90–100 thousand years old (Erlykin & Wolfendale 2003). If such a strong cosmic-ray accelerator lies near the Earth, we may observe an anisotropy of cosmic rays from its direction, or we may detect high-energy photons that are emitted from these high-energy charged particles by the nonthermal processes.

In this paper, we report on the search for diffuse/pointlike PeV gamma-ray emission based on the data recorded from 1997 to 2004 around the Monogem ring region by a large air shower array with a total area of 36,900 m^2 constructed in Tibet.

2. Experiment

The Tibet air shower experiment has been successfully operated at Yangbajing (E90°31′, N30°06′; 4300 m above sea level) in Tibet, China since 1990. The Tibet I array was constructed in 1990 (Amenomori et al. 1992) and it was gradually expanded by 1994 to the Tibet II that consisted of 185 fast-timing (FT) scintillation counters placed on a 15 m square grid covering 36,900 m^2 and 36 density (D) scintillation counters around the FT-counter array. Each counter has a plastic scintillator plate (BICRON BC-408A) of 0.5 m^2 in area and 3 cm in thickness. A 0.5 cm thick lead plate is put on the top of each counter in order to increase the counter sensitivity by converting gamma rays into electron-positron pairs in an electromagnetic shower (Bloomer, Linsley, & Watson 1988; Amenomori et al. 1990). All the FT counters are equipped with a fast-timing photomultiplier tube (FT-PMT; Hamamastu H1161) measuring up to 15 particles, and 52 out of 185 FT counters, which are arrayed at 30 m lattice intervals, are also equipped with a wide dynamic range PMT (D-PMT; Hamamatsu H3178) measuring up to 500 particles. The time and charge information of the FT-PMTs is recorded, while only the charge information of D-PMT is recorded. All the D counters are also equipped with FT-PMT and D-PMT, where only charge information of both PMTs is recorded. An event trigger signal is issued when any fourfold coincidence occurs in the FT counters recording more than 0.6 particles. The mode of energy of the triggered events in Tibet II is $\sim$10 TeV.

From 1996 to 2003, we upgraded the array, and, at present, it consists of 761 FT counters covering 50,400 m^2 and 28 D counters around them. In the inner 36,900 m^2, FT

counters are deployed at 7.5 m lattice intervals. Since 1999 October, we have called this upgraded array Tibet III. The mode of energy of the triggered events in Tibet III is 3 TeV. Using Tibet III, we observed the multi-TeV gamma-ray flares from Mrk 421 in 2000 and 2001 (Amenomori et al. 2003a) and the cosmic-ray anisotropy (Amenomori et al. 2004; Amenomori et al. 2005a), surveyed the northern TeV gamma-ray sky (Amenomori et al. 2005b), and measured the all-particle energy spectrum (Amenomori et al. 2003b) and chemical composition of the cosmic rays in the knee region (Amenomori et al. 2003c).

3. Analysis

In the present paper, we employ the data obtained by the 185 FT counters and the 36 D counters corresponding to the Tibet II array configuration for the whole period in order to simplify the analysis. We collected 1.6×10^8 air shower events during 1717 detector live days from 1997 February 15 to 2004 October 10 after the quality cut and the event selection based on the following simple criteria:

1. *Airshowercorelocation.*—Among the three hottest counters in each event, two should be contained in the inner 36,900 m^2.
2. *Showersize.*—$\Sigma\rho_{\rm D}$ which is the sum of the number of particles per m^2 counted by the 36 D counters and 52 out of 185 FT counters that have a D-PMT, should be more than 100.
3. *Zenithangle.*— The zenith angle of the arrival direction should be less than 40°.

To examine the performance of the Tibet II array, we use a Monte Carlo (MC) simulation. We employ the CORSIKA version 6.200 code (Heck et al. 1998) for the generation of air shower events and the EPICS uv8.00 code (K.Kasahara 2005)[1] for the detection of shower particles with scintillation counters, respectively. The primary gamma rays are sampled from the Monogem ring orbit assuming a differential power-law spectrum with spectral index −2.0 from 10 TeV to 30 PeV.

According to the MC simulation including the quality cut and the event selection, the mode energy of gamma rays is 150 TeV, the angular resolution is less than 0.°3, and the effective area for gamma rays is nearly 2.5×10^4 m^2 for a 3° × 3° search window in a diffuse source analysis and 1.6×10^4 m^2 for a 0.°5 × 0.°5 search window in a pointlike source analysis. The gamma-ray energy is estimated from $\Sigma\rho_{\rm D}$ by the MC simulation and the energy resolution is less than 30% above 150 TeV. The systematic pointing error is estimated to be

[1]Additional information on Kasahara (2005) is available at http://eweb.n.kanagawa-u.ac.jp/~kasahara/ResearchHome/EPICSHome/.

less than $0.^\circ 02$ by the Moon's shadow in cosmic rays (Amenomori et al. 2003a). The source positional uncertainty is typically less than $0.^\circ 1$ at 150 TeV for gamma rays, assuming a 5 σ significance level. The center of the Monogem ring ($\delta = 14^\circ$) stays in the field of view (with a zenith angle of $<40^\circ$) for 380 days out of 1717 live days.

Subsequently, we use the right ascension scan method to search for PeV gamma-ray sources that follows the same analysis method and parameters employed by the MAKET-ANI experiment (Chilingarian, Martirosian, & Gharagyozyan 2003). First, each event is sorted by its arrival right ascension and declination into a $\Delta\alpha \times \Delta\delta = 3^\circ \times 3^\circ$ rectangular cell. Off-source events are taken from all the cells (except the on-source cell) in the same declination band as the on-source cell. The significance of the source in each cell is calculated based on exsquation (17) of Li & Ma (1983).

We scanned the celestial sky in the declination band from $-5.^\circ 5$ to $66.^\circ 5$ in the whole right ascension range 0° – 360°. We also scanned the whole Monogem ring region and the region around it in the declination band from 0° to 30° in the right ascension range 80° – 130° with a $\Delta\alpha \times \Delta\delta = 0.^\circ 5 \times 0.^\circ 5$ search window analysis for a pointlike source.

4. Results

Figure 1 shows the number of events in each of the 120 cells in the declination band $12.^\circ 5$–$15.^\circ 5$ by the $\Delta\alpha \times \Delta\delta = 3^\circ \times 3^\circ$ search window analysis with $\Sigma\rho_{\mathrm{D}} > 1000$ (corresponding to $>$ 1 PeV). The shaded histogram denotes our actual result, and the dashed one is the expected excess from the MAKET-ANI result. The MAKET-ANI experiment detected a significant excess in the direction $111^\circ \leq \alpha < 114^\circ$, $12.^\circ 5 \leq \delta < 15.^\circ 5$ at the 6 σ statistical significance. But no significant signal was detected by the Tibet air shower array(-0.6σ). It should be noted that the Tibet air shower array accumulated about 100 times as much statistics as the MAKET-ANI experiment, corresponding to an approximately 10 times better sensitivity, which is easily calculated by the number of background events as summarized in Table 1. In addition, the significance distribution as shown in Figure 2 implies the absence of such a bright and diffuse source above 1 PeV, even in the all sky survey ($0^\circ \leq \alpha < 360^\circ$, $-5.^\circ 5 \leq \delta < 66.^\circ 5$).
Taking the pointing errors of both experiments into account, we scanned the area of $\alpha \pm 5^\circ$, $\delta \pm 5^\circ$ around the source direction claimed by the MAKET-ANI experiment by sliding the center of the $3^\circ \times 3^\circ$ search window by $0.^\circ 5$ steps in right ascension and declination; however, no significant excess was found again.

Table 1 demonstrates the energy dependence of the result in the region suggested by the

MAKET-ANI experiment by the $3^\circ \times 3^\circ$ search window analysis, also confirming no signal detection. As the MAKET-ANI experiment detected a significant excess in the various energy thresholds of >800 TeV, >1 PeV, and >2 PeV, we would have detected a significant signal at $50 \pm 10\ \sigma$ (estimated from the number of on-source and off-source events based on equation (17) of Li & Ma (1983), which is a different definition from MAKET-ANI's) in at least one energy threshold even if the relative energy scale uncertainty between the two experiments differed by a factor of 2.

Figure 3 shows the significance map of the whole Monogem ring region and the region around it ($80^\circ \leq \alpha < 130^\circ$, $0^\circ \leq \delta < 30^\circ$) based on a finer window search of $0\overset{\circ}{.}5 \times 0\overset{\circ}{.}5$ cells at energies > 1 PeV. Again, no significant signal was found. There are two directions with a significance $> 4\sigma$ at $(\alpha, \delta) = (108\overset{\circ}{.}75, 18\overset{\circ}{.}75)$, $(120\overset{\circ}{.}25, 12\overset{\circ}{.}75)$ that are very far from the point where the MAKET-ANI experiment claimed the detection of a signal. The expected number of directions above 4σ in a normal Gaussian distribution with 6000 trials is 0.19, and the probability of getting more than 2 in a Poisson distribution with mean value of 0.19 is 1.6×10^{-2}. Therefore, the deviation may be due to statistical fluctuations. The results of the $0\overset{\circ}{.}5 \times 0\overset{\circ}{.}5$ window searches did not show any significant energy dependence, and no significant deviation of significance distribution from a normal Gaussian distribution was found at the other energy thresholds (> 500 TeV, > 800 TeV, and > 2 PeV).

5. Discussions

No evidence for statistically significant gamma-ray signals was found in a region $111^\circ \leq \alpha < 114^\circ$, $12\overset{\circ}{.}5 \leq \delta < 15\overset{\circ}{.}5$ in the Monogem Ring where the MAKET-ANI experiment recently claimed a positive detection of PeV high energy cosmic radiation, although our flux sensitivity is approximately 10 times better than MAKET-ANI's. We set the most stringent integral flux upper limit at a 99% confidence level of 1.1×10^{-14} cm^{-2}s^{-1}/(2.66×10^{-3}sr) $= 4.0 \times 10^{-12}$ cm^{-2} s^{-1} sr^{-1} on steady diffuse gamma rays > 1 PeV extended within the rectangular region in the Monogem Ring assuming a differential spectral index -2.0. One of the potential possibilities for explaining the discrepancy between the two experiments could be transient emission that occurred at occasions when we stopped data acquisition for annual maintenance, calibration, upgrading jobs, etc. Another could be the strong transient emission of PeV gamma rays that incidentally or periodically occurred during the 3 hr when only the MAKET-ANI experiment could observe because the two experimental sites are separated by about 45° in longitude. Third, the excess events that they detected might be due to statistical fluctuation (Chilingarian et al. 2005).

No significant signal was found in the whole Monogem Ring region based on a $0\overset{\circ}{.}5 \times 0\overset{\circ}{.}5$

window search for a pointlike source at energies > 1 PeV. We also set 99% confidence-level flux upper limits of 2.6 and 5.4×10^{-15} cm^{-2} s^{-1} on the steady gamma rays > 1 PeV from PSR B0656+14 and Geminga, respectively, assuming pointlike sources with a differential energy spectral index −2.0. The KASCADE group also reported that no significant signal was seen in the sub-PeV region at the suggested location by the MAKET-ANI experiment and PSR B0656+14 by a pointlike source analysis (Antoni et al. 2004). Furthermore, we reported on the result of wide sky survey for steady TeV gamma-ray pointlike sources elsewhere (Amenomori et al. 2005b), although no significant point source was found in the Monogem Ring region above a few TeV and above 10 TeV.

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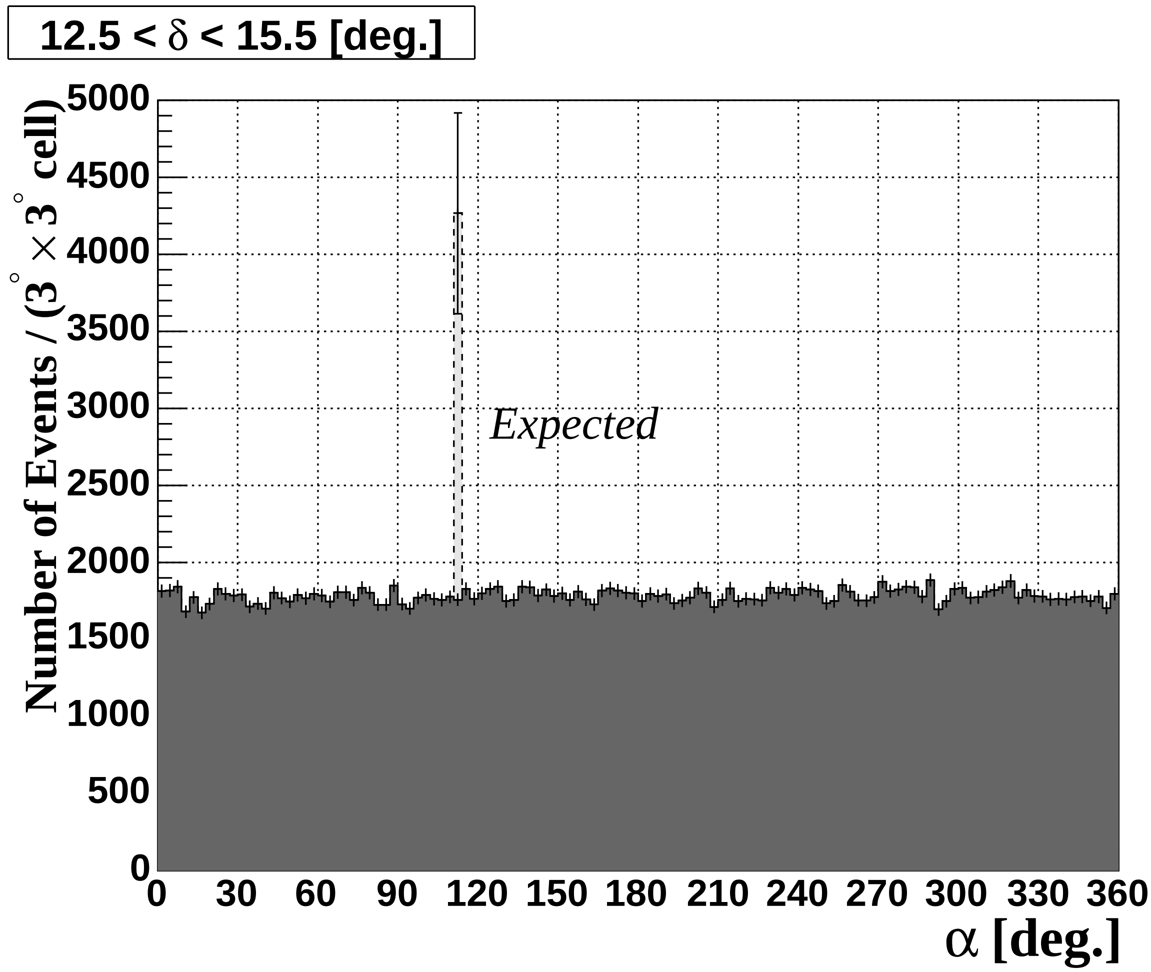

Fig. 1.— Number of events above 1 PeV in each of the 120 cells in the declination band of 12°.5–15°.5 observed by the Tibet air shower array during 1717 live days from 1997 February 15 to 2004 October 10. The shaded histogram represents our actual result, while the dashed histogram denotes the number of events expected from the MAKET-ANI result (Chilingarian, Martirosian, & Gharagyozyan 2003).

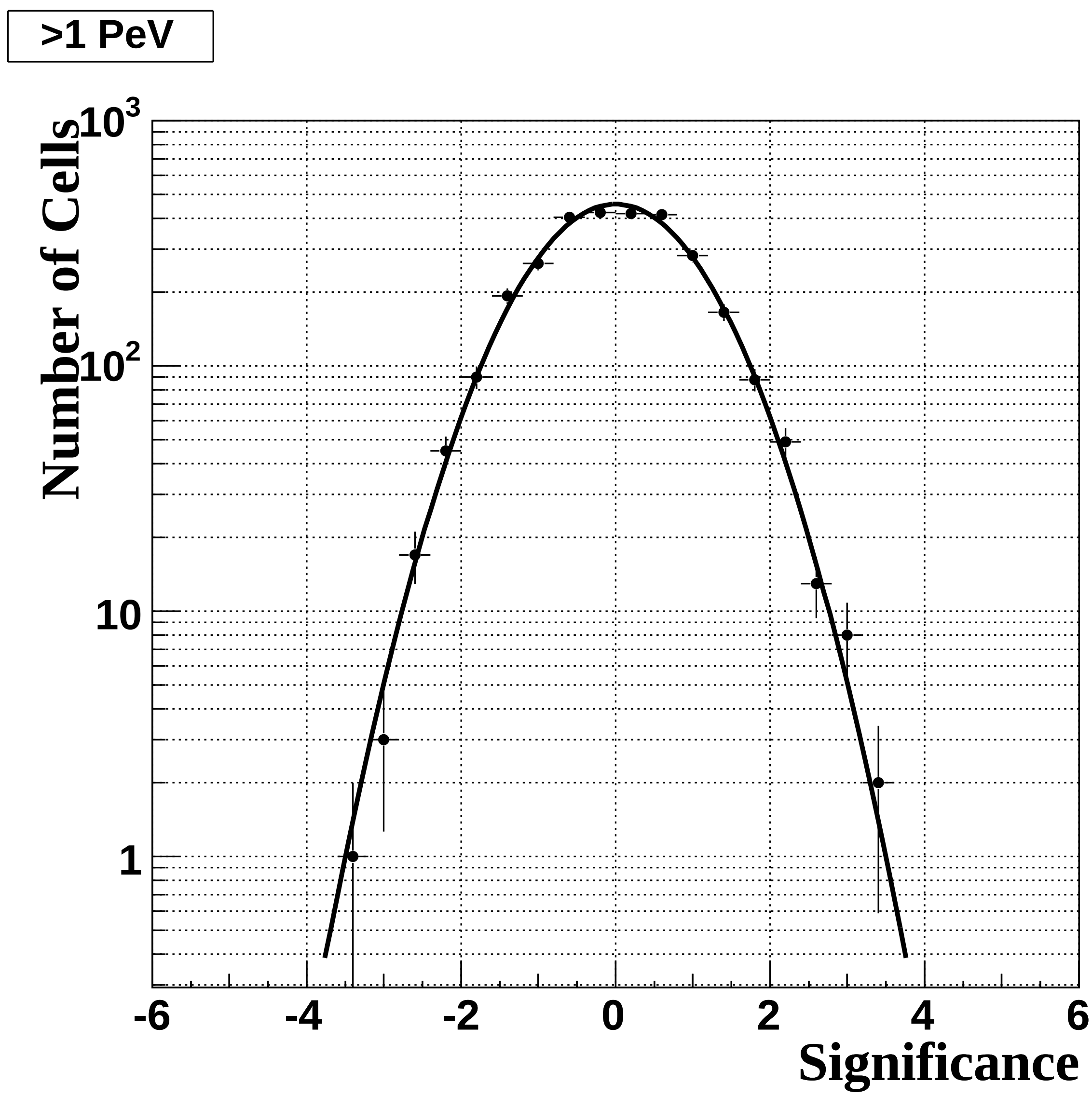

Fig. 2.— Significance distribution of 2880 $\Delta\alpha \times \Delta\delta = 3^\circ{\times}3^\circ$ cells in the declination band $-5\overset{\circ}{.}5 \leq \delta < 66\overset{\circ}{.}5$ above 1 PeV. Each cell is independent of one another. The solid line indicates a normal Gaussian fit to the data.

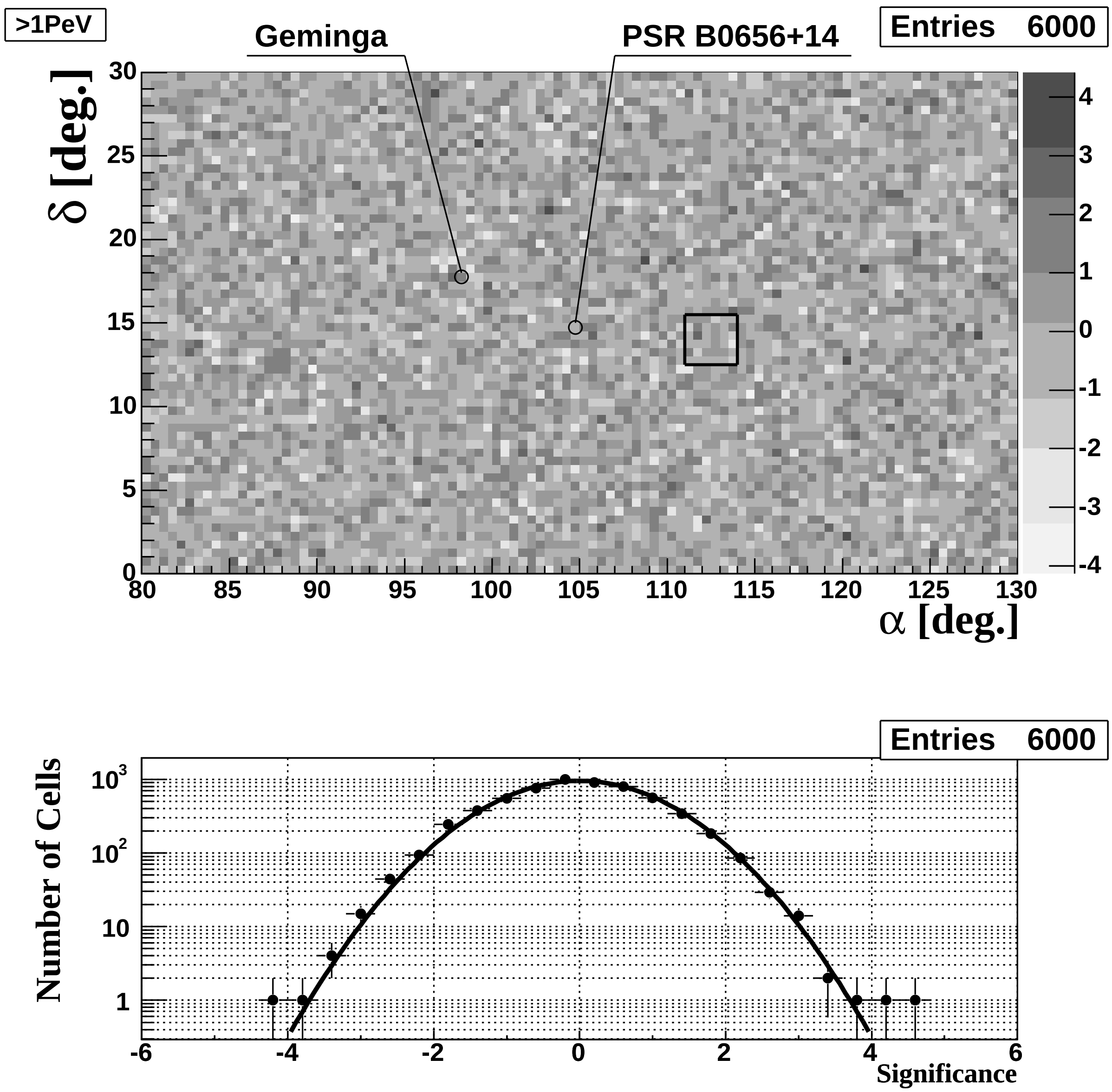

Fig. 3.— *Top*: Significance map in the Monogem Ring region and the region around it above 1 PeV. Each cell is independent of one another. PSR B0656+14 is located at the center of the region. The rectangular region indicates the area where the MAKET-ANI experiment claimed a positive detection of a signal. *Bottom*: Significance distribution in the region shown in the map. The solid line indicates a normal Gaussian fit to the data. The two cells with $> 4\ \sigma$ are located at $(\alpha, \delta) = (108.^\circ 75,\ 18.^\circ 75)$ and $(120.^\circ 25,\ 12.^\circ 75)$, respectively.

Table 1. Enegy dependence of the number of events in the cell $111^\circ \leq \alpha < 114^\circ$, $12\overset{\circ}{.}5 \leq \delta \leq 15\overset{\circ}{.}5$ ($N^{\rm ON}$) and the background ($N^{\rm BG}$)

Primary Gamma-ray Energy[a] [TeV]	$N_{\rm Tibet}^{\rm BG}$ [b]	$N_{\rm Tibet}^{\rm ON}$	$N_{\rm MAKET}^{\rm BG}$ [b]	$N_{\rm MAKET}^{\rm ON}$
>500	5664.7	5605	58	84
>800	2609.6	2618	26	57
>1000 ($N_e > 10^6$)	1785.9	1759	18	43
>2000	506.3	490	4	13

[a]The primary gamma-ray energy of the MAKET-ANI experiment was estimated by the air shower size reported in (Chilingarian, Martirosian, & Gharagyozyan 2003), where $N_e > 10^6$ at MAKET-ANI altitude corresponds to >1 PeV (Erlykin & Wolfendale 2004) and where we scaled the other energies, while that of the Tibet air shower array is estimated by the air shower size $\Sigma\rho_{\rm D}$, described in the text, in the Tibet air shower array.

[b]Mean value of the background cells in the declination band $12\overset{\circ}{.}5 \leq \delta \leq 15\overset{\circ}{.}5$. Subscripts "Tibet" and "MAKET" represent our result and the MAKET-ANI result, respectively.